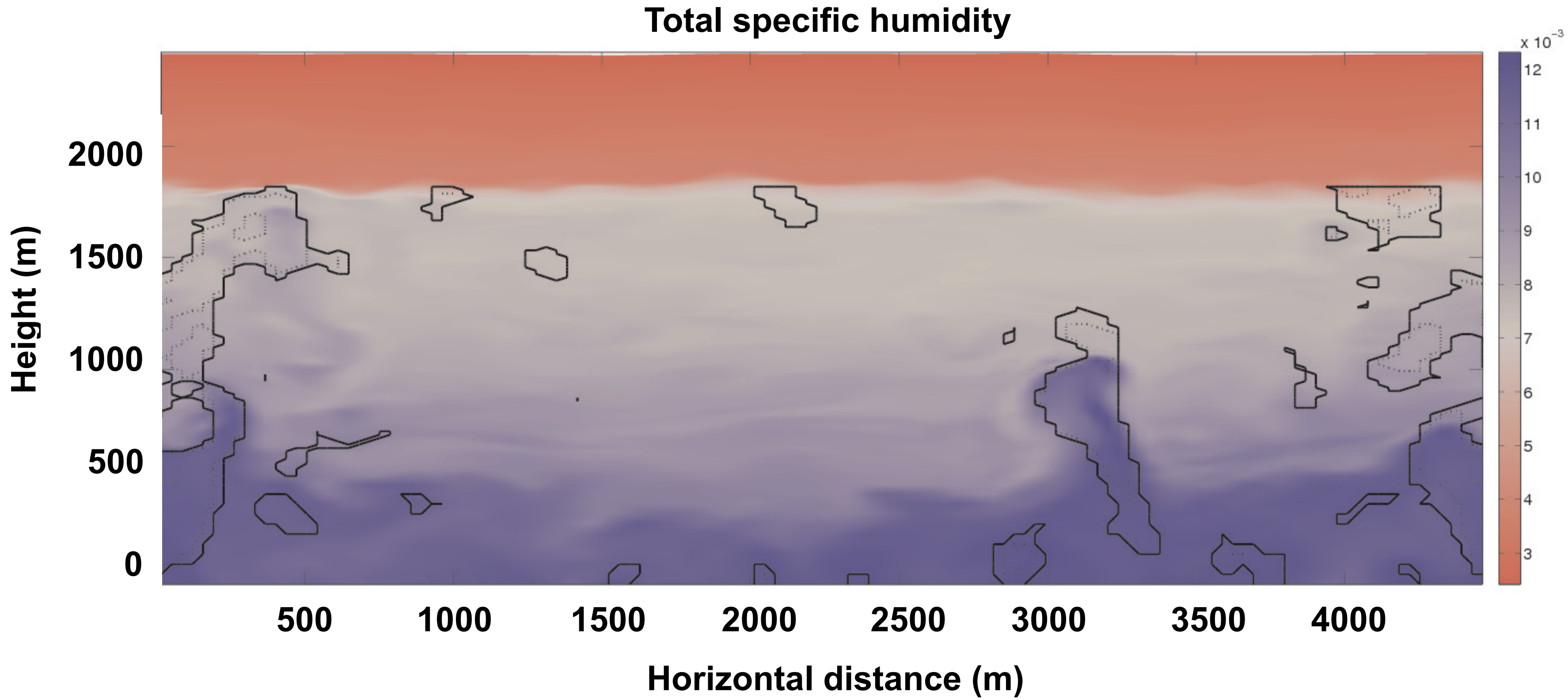
LES results of the EUCLIPSE-GASS Lagrangian cloud transition cases:

Decoupling and entrainment



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Pier Siebesma, Bjorn Stevens,

Andy Ackerman, Peter Blossey, and Adrian Lock

Schematic of cumulus penetrating stratocumulus

(Stevens et al, based on ATEX intercomparison case)

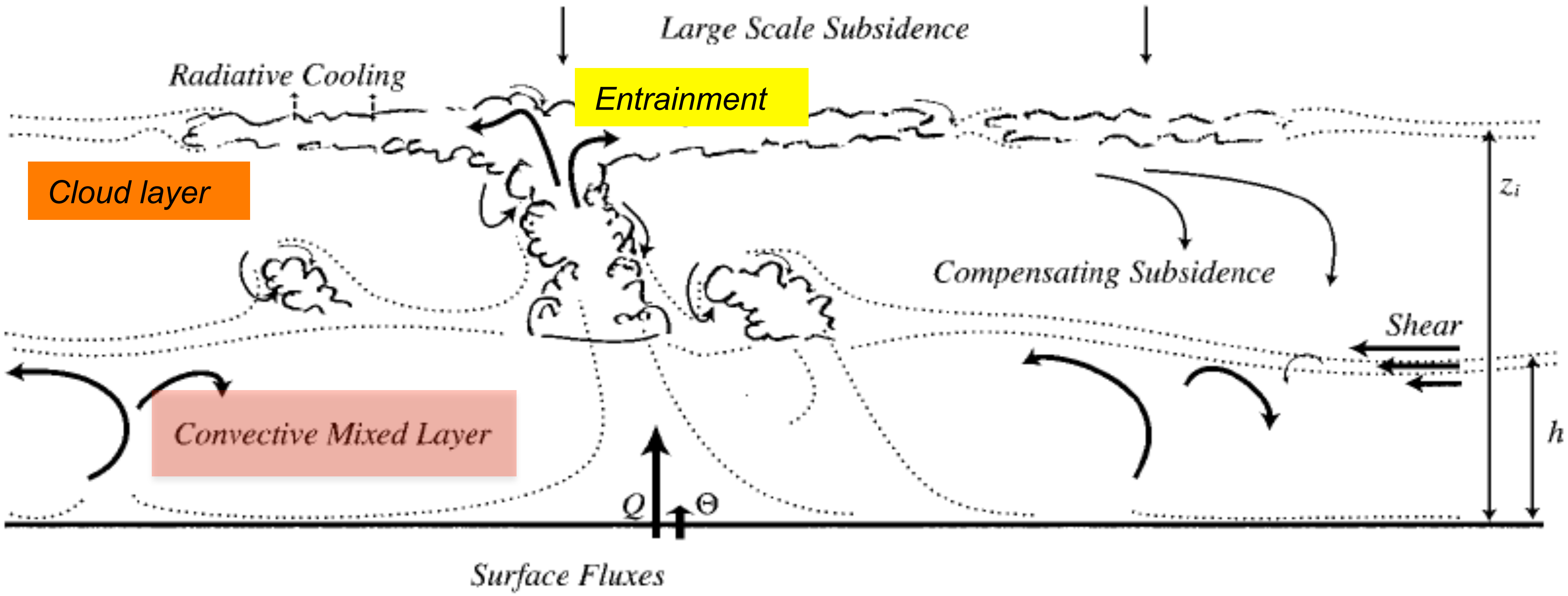
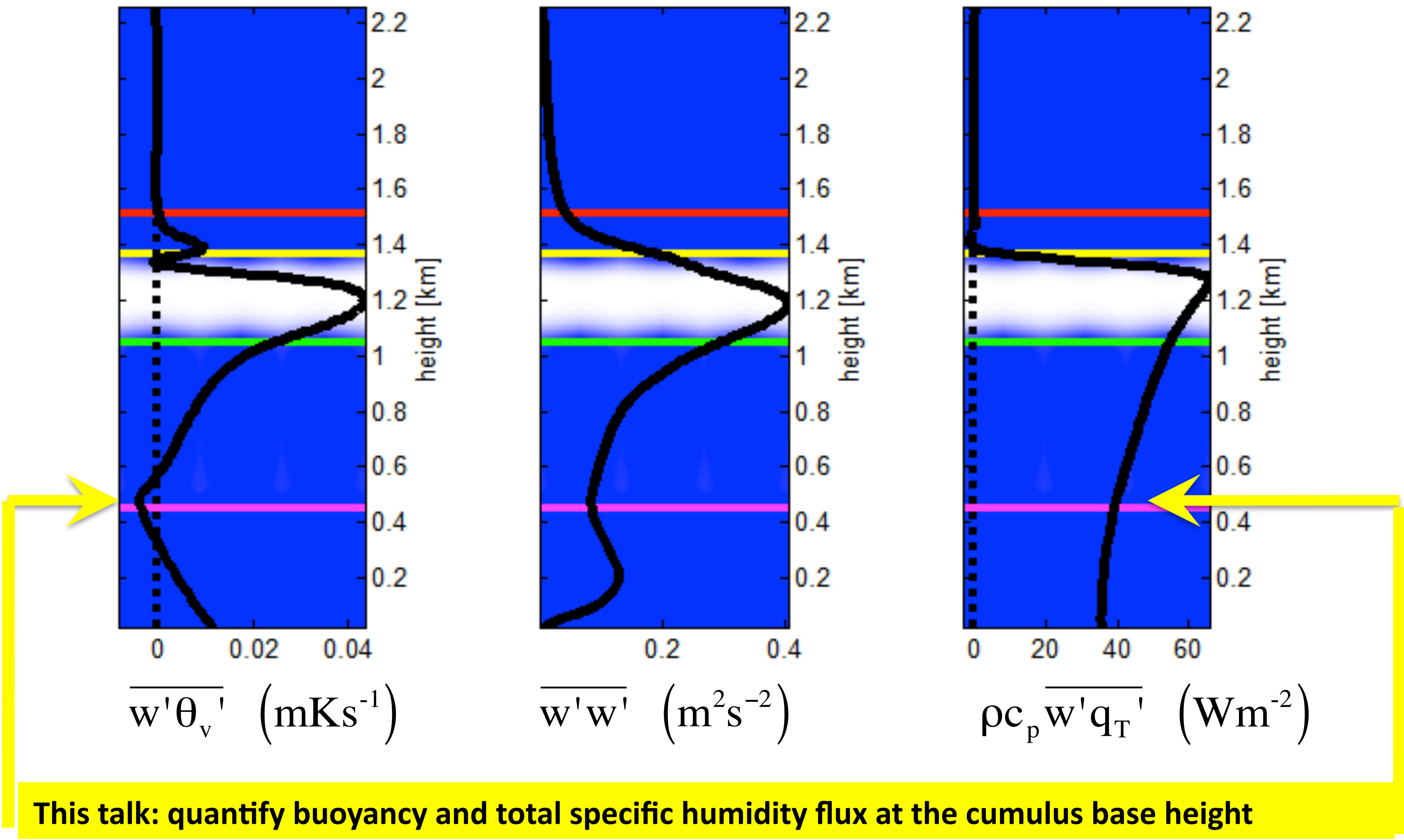


FIG. 14. Conceptual diagram of intermediate trade cumulus regime.

- Boundary layer is decoupled
- Subcloud layer dynamics scale like dry convective boundary layer

Example: Turbulent fluxes in ASTEX from DALES at t=23 hr



Plots courtesy Coen Hennipman

Questions

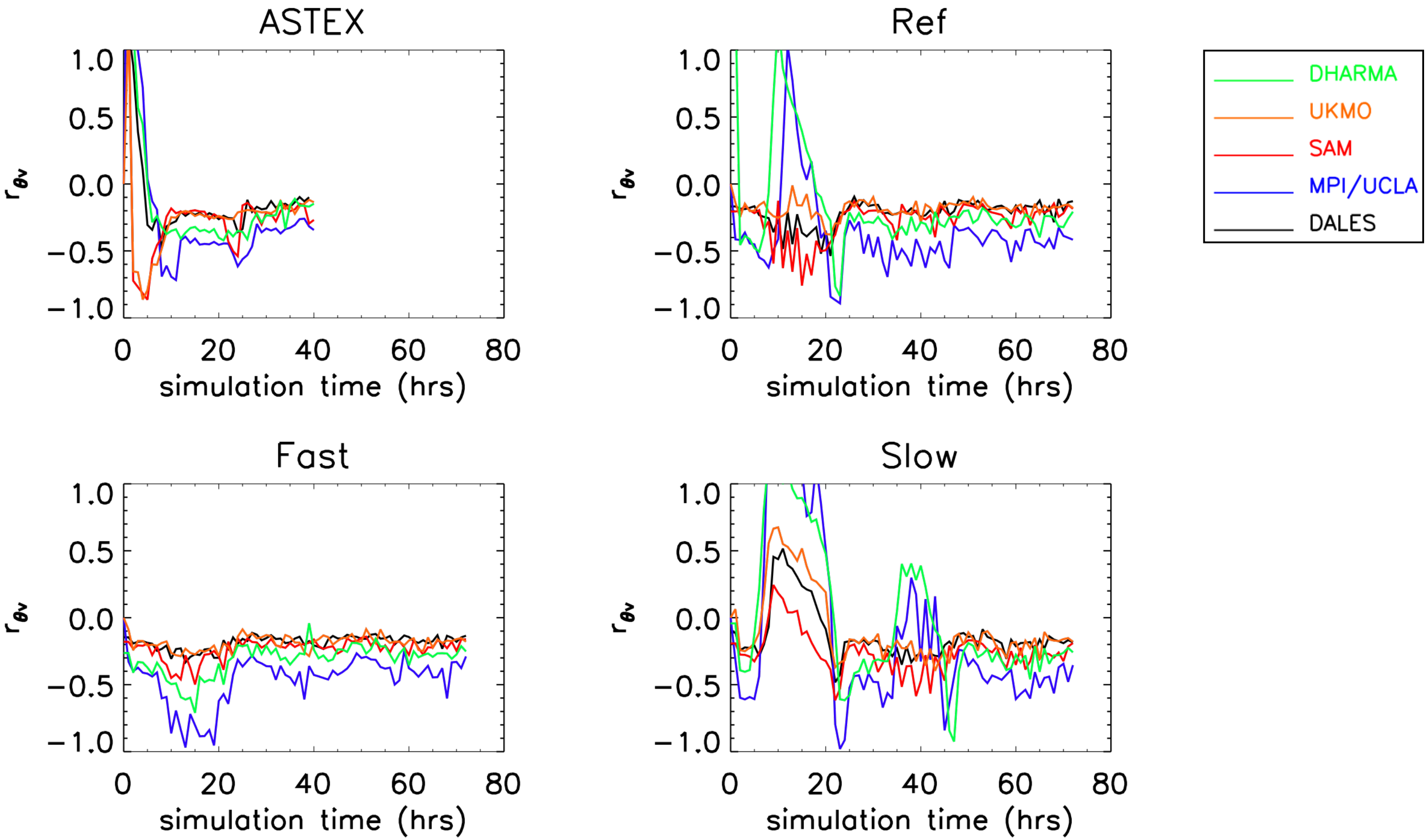
- How much moisture is transported out of the subcloud layer by shallow cumuli

- Magnitude of cloud-top entrainment rate

Strategy

- Use simple analytical considerations as a guidance to interpret the LES results

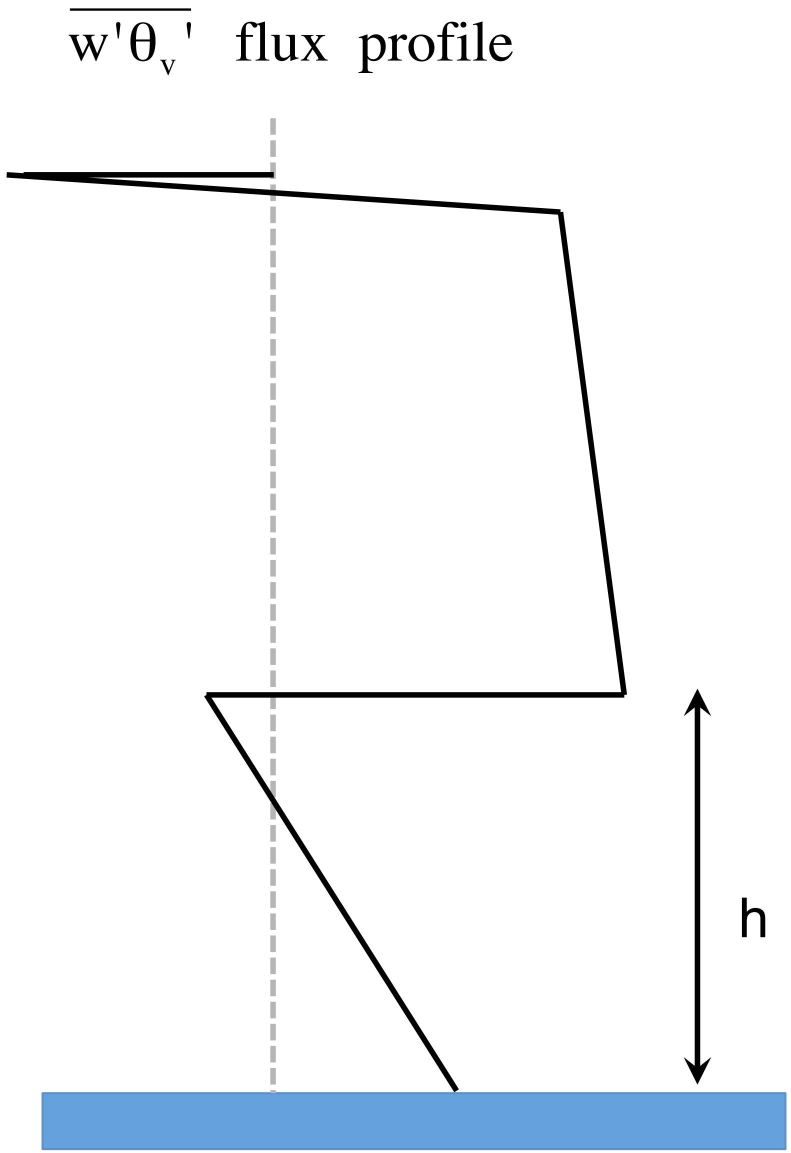
After some time, buoyancy flux ratio $r_{\theta v}$ becomes close to CBL value



$$r_{\theta_v} = \frac{\overline{w'\theta_v'}_{min}}{\overline{w'\theta_v'}_{sfc}}$$

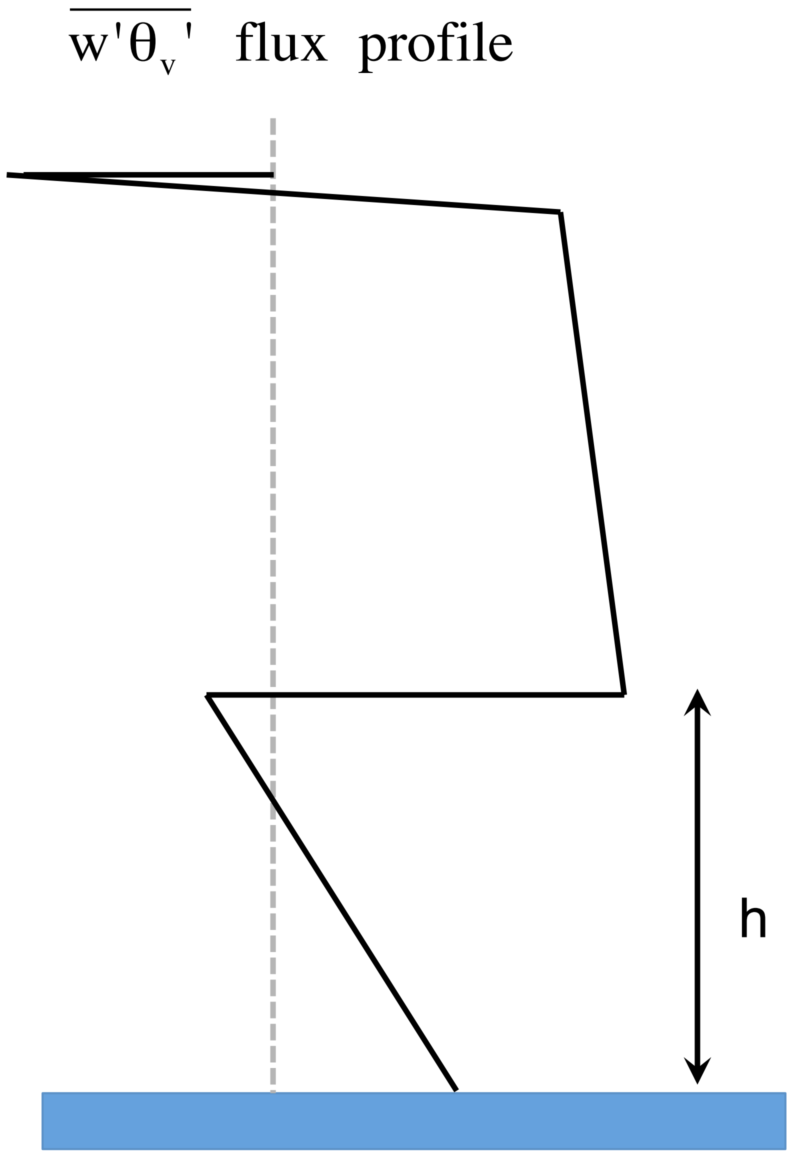
CBL value ≈ -0.2

Virtual potential temperature evolution in the subcloud layer



$$\overline{w'\theta_v'}_0 = c_D U_{ML}\left(\theta_{v,0} - \theta_{v,ML}\right)$$

Virtual potential temperature evolution in the subcloud layer

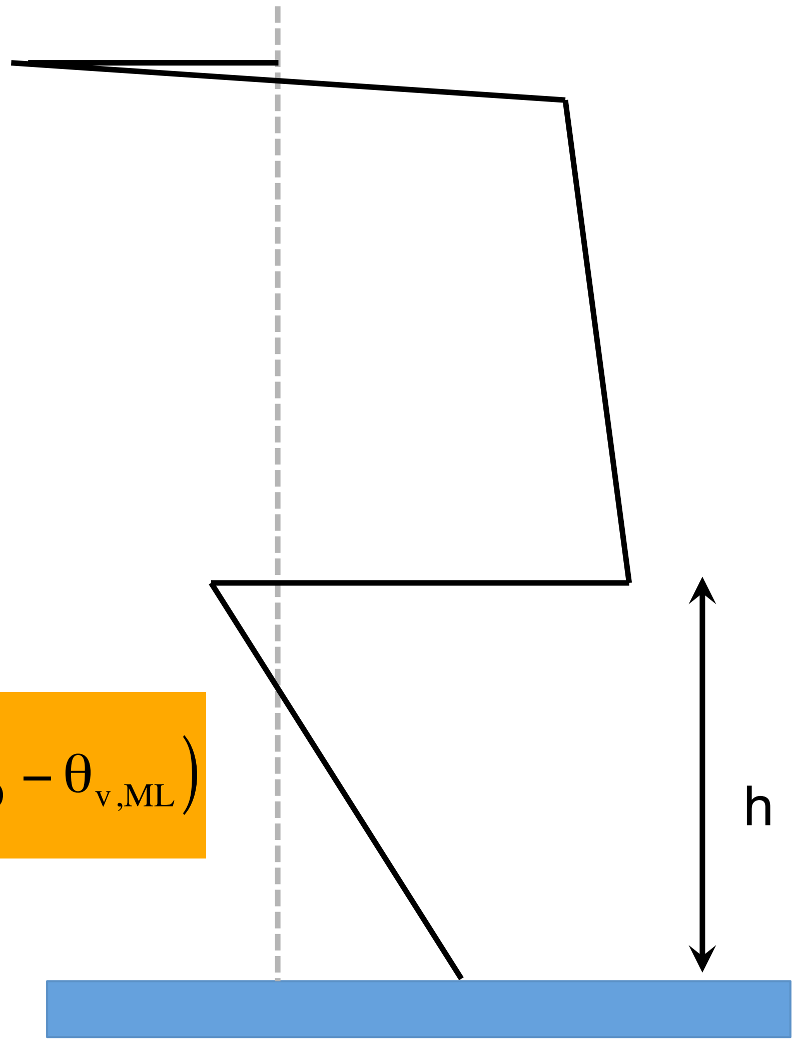


$$\overline{w'\theta_v'}_h = r_{\theta_v}\overline{w'\theta_v'}_0$$

$$\overline{w'\theta_v'}_0 = c_D U_{ML}\left(\theta_{v,0} - \theta_{v,ML}\right)$$

Virtual potential temperature evolution in the subcloud layer

$\overline{w'\theta_v'}$ flux profile



$$\overline{w'\theta_v'}_h = r_{\theta_v}\,\overline{w'\theta_v'}_0$$

$$\frac{\partial\theta_{v,ML}}{\partial t} = -\frac{\partial\overline{w'\theta_v'}}{\partial z} = \left(\frac{1-r_{\theta_v}}{h}\right)c_D U_{ML}\left(\theta_{v,0}-\theta_{v,ML}\right)$$

$$\overline{w'\theta_v'}_0 = c_D U_{ML}\left(\theta_{v,0}-\theta_{v,ML}\right)$$

Assume SST increases linearly with time (and likewise $\theta_{v,0}$)

1. Time-dependent BC: $\theta_{v,0}(t) = \theta_{v,00} + \gamma t$

2. Assume constant subcloud layer height h

Solution $$\theta_{v,ML}(t) = a + \underbrace{\gamma t}_{\text{linear term}} + \underbrace{b e^{-t/\tau_{\theta_v}}}_{\text{"memory term"}}$$

$$a = \theta_{v,00} - \gamma\tau_{\theta_v}$$

$$b = \gamma\tau_{\theta_v} + \theta_{v,ML}\Big|_{t=0} - \theta_{v,00}$$

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If **h = 500 m, $r_{\theta v}$ = -0.2, c_D=0.001, U_{ML} = 10 m/s then**

$$\tau_{\theta_v} = \frac{h}{c_D U_{ML}\left(1 - r_{\theta_v}\right)} \approx 1/2 \text{ day}$$

Similar approach for the subcloud humidity
Surface saturation specific humidity obeys Clausius-Clapeyron

Time-dependent BC

$$q_{s,0}(t) = q_{s,0}\Big|_{t=0} e^{t/\tau_{cc}}$$

Solution

$$q_{v,ML}(t) = a_q q_{s,0}(t) + \underbrace{b_q e^{-t/\tau_q}}_{\text{"memory term"}}$$

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Surface saturation specific humidity obeys Clausius-Clapeyron

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Solution

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$$a_q = \frac{1}{1 + \frac{\tau_q}{\tau_{cc}}} \leq 1$$

subcloud humidity tendency typically smaller than tendency of $q_{sat,sfc}$ at the sea surface

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Clausius-Clapeyron time scale:

$$\tau_{cc} = \frac{R_v \left(T_0\big|_{t=0}\right)^2}{L_v \gamma} \approx 5 \text{ days}$$

turbulence time scale:

$$\tau_q = \frac{h}{c_D U_{ML}\left(1 - r_{q_v}\right)}$$

Similar approach for the subcloud humidity
Surface saturation specific humidity obeys Clausius-Clapeyron

Time-dependent BC

$$q_{s,0}(t) = q_{s,0}\big|_{t=0} e^{t/\tau_{cc}}$$

Solution

$$q_{v,ML}(t) = a_q q_{s,0}(t) + \underbrace{b_q e^{-t/\tau_q}}_{\text{"memory term"}}$$

$$a_q = \frac{1}{1+\frac{\tau_q}{\tau_{cc}}} \le 1$$

subcloud humidity tendency typically smaller than tendency at the sea surface

$$b_q = q_{v,ML}\big|_{t=0} - \frac{q_{s,0}\big|_{t=0}}{1+\frac{\tau_q}{\tau_{cc}}}$$

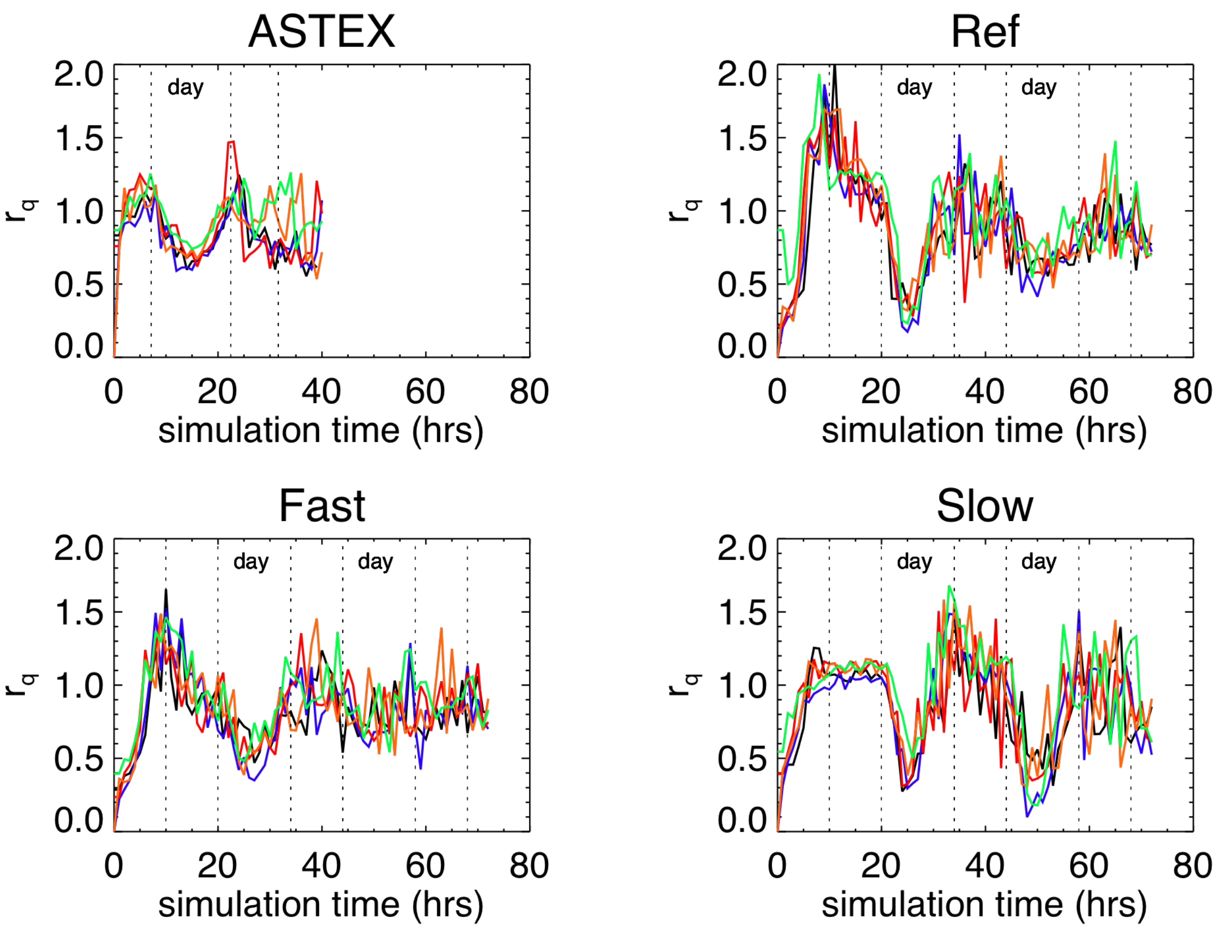
Clausius-Clapeyron time scale:

$$\tau_{cc} = \frac{R_v \left(T_0\big|_{t=0}\right)^2}{L_v \gamma} \approx 5 \text{ days}$$

turbulence time scale:

$$\tau_q = \frac{h}{c_D U_{ML}\left(1-r_{q_v}\right)}$$

Diurnal cycle of moisture flux at the top of the subcloud layer



$$r_q = \frac{\overline{w'q_T'}_{z=z_{\overline{w'\theta_v'}min}}}{\overline{w'q_T'}_{sfc}}$$

* Weakening of moisture transport at cumulus cloud base during day-time

* During the night cumulus are more actively removing moisture from subcloud layer

* Mean value r_q slightly smaller than 1

Subconclusion

Decoupled subcloud layer:

$\theta_{v,ML}$ follows warming tendency of the SST

Question: what about cloud layer?

*** Net cooling due to longwave radiative loss**

*** Entrainment warming**

Idea: diagnose entrainment rate that is "needed" to give the same heating tendency in the subcloud and cloud layers
(in other words, check if boundary layer is in a quasi-steady state)

What is the entrainment rate needed to give a quasi-steady state

(this means θ_{LV} tendency in the cloud is similar to the subcloud layer)

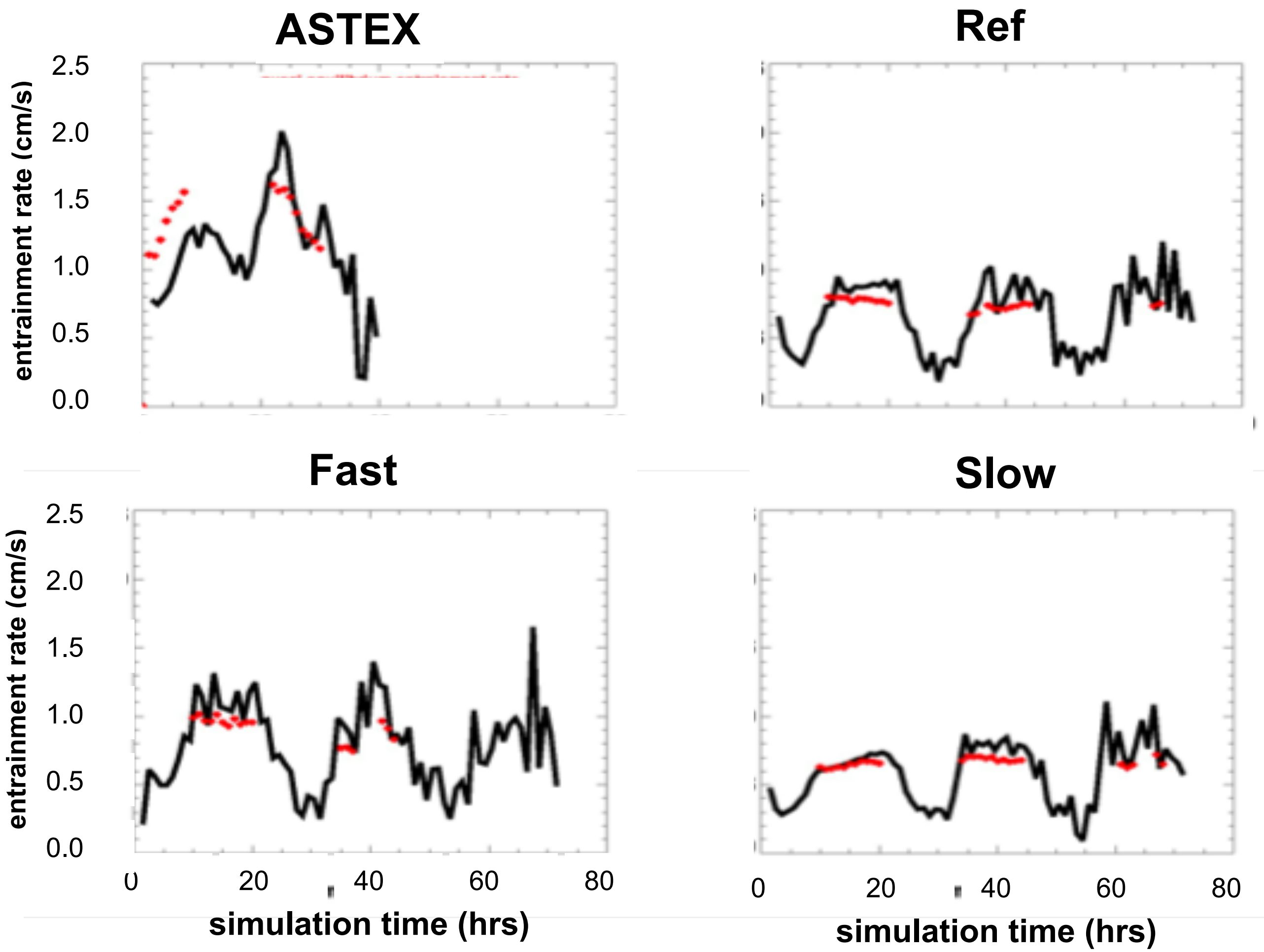
$$\frac{\partial \theta_{VL}}{\partial t} = -\frac{\partial \overline{w'\theta'}_{VL}}{\partial z} - \frac{1}{\rho c_p}\frac{\partial F}{\partial z} \quad , \quad \theta_{VL} = \theta_L\left(1 + 0.61 q_v - q_L\right)$$

$$\frac{\partial \theta_{VL,CLD}}{\partial t} = \left(\frac{\partial \theta_{VL}}{\partial t}\right)_{subcloud} \approx \frac{w_e \Delta\theta_{VL}}{z_i - h} - \frac{1}{\rho c_p}\frac{\Delta F}{z_i - h}$$

$$w_e = \frac{z_i - h}{\Delta\theta_{VL}}\left(\frac{\partial \theta_{VL}}{\partial t}\right)_{subcloud} + \frac{1}{\rho c_p}\frac{\Delta F}{\Delta\theta_{VL}}$$

Black lines: DALES entrainment rates

Red dots: diagnosed 'quasi-equilibrium' entrainment rate during the night in solid stratocumulus clouds



Conclusions

Dynamics in a decoupled subcloud layer similar to the dry CBL

Decoupling makes it easier to understand subcloud layer dynamics

-> subcloud temperature tends to follow the time-varying SST

Humidity flux at the top of the subcloud layer exhibits a distinct diurnal cycle

-> Strong cumulus transport during the night, and much smaller during day-time (moisture build-up)

-> on average, nearly all moisture that is evaporated from the surface is transported to the stratocumulus

so cumulus clouds support the persistence of the stratocumulus

During night-time quasi-steady state boundary layer

-> during nighttime, entrainment rate controled by SST tendency, LW cooling, and inversion jump of temperature?